IMECE'99 - International Mechanical Engineering, ASME, Topic: Recent Advances of Ultrasonic NDE, Nashville, TN, Nov. 14-19, 1999

PROGRESS AND CHALLENGES TO NDE OF COMPOSITES USING OBLIQUELY INSONIFIED ULTRASONIC WAVES

Yoseph Bar-Cohen, Shyh-Shiuh Lih and Zensheu Chang
Jet Propulsion Laboratory, Caltech, MS 82-105, 4800 Oak Grove Dr., Pasadena, CA 91109-8099, 818-394-2610, fax 818-393-4057, yosi@jpl.nasa.gov

ABSTRACT

The use of obliquely insonified ultrasonic waves has shown great promise in providing information about flaw characteristics and material properties of composite materials. Polar Backscattering and Leaky Lamb Waves (LLW) are techniques that employ oblique insonification, where either a single transducer as transmitter/receiver or a pitch-catch arranged transducer pair are used, respectively. These two techniques rely on phenomena that were discovered in 1979 and 1982, respectively, and they have shown significant NDE capabilities and potential for composite materials, bonded joints and other applications. The LLW phenomenon in particular has been studied extensively, both through theoretical modeling and laboratory tests, and the behavior in multi-orientation laminates is now relatively well understood. In spite of the theoretical and experimental progress, methods that employ oblique insonification are still not being applied as standard industrial NDE tools for structural composites. The authors have identified four key issues that need to be addressed in order to improve the practical usefulness of the LLW. Further, the authors made recently significant improvements of the experimental procedures enhancing the speed and accuracy of data acquisition, which is one of the four issues. The oblique insonification experimental progress and challenges to NDE of composites will be reviewed and discussed in this manuscript.

INTRODUCTION

The high stiffness to weight ratio, low electromagnetic reflectance and the ability to embed sensors and actuators have made fiber-reinforced composites an attractive construction material for primary aircraft structures. These materials consist of fibers and a polymer matrix that are stacked in layers and then cured. A limiting factor in the widespread use of composites is their high cost - composite parts are about an order of magnitude more expensive than metallic parts. The cost of inspection is about 30% of the total cost of acquiring and operating composite structures. This large portion of the total cost makes the need for effective inspection critical not only for operational safety but also for cost effectiveness of these materials [Bar-Cohen, et al, 1991]. A series of needs/issues are still challenging the NDE research community with regards to inspection of composite materials and they include: effective defect detection and characterization, determination of material properties in multilayered laminates, rapid large area inspection methods, real-time health monitoring, and residual stress measurement capability. Generally, NDE methods are used to determine the integrity and stiffness of composite structures. While information about the integrity and stiffness can be extracted directly from NDE measurements, strength and durability can not be measured by such measurements because these are not physically measurable parameters. For many years, the multi-layered anisotropic nature of composites posed a challenge to the NDE research community. Pulse-echo and through-transmission are still the leading standard NDE methods of determining the quality of composites. However, these methods provide limited and mostly qualitative information about defects and material properties. The discovery of the leaky Lamb wave (LLW) [Bar-Cohen & Chimenti, 1984] and the Polar Backscattering [Bar-Cohen &

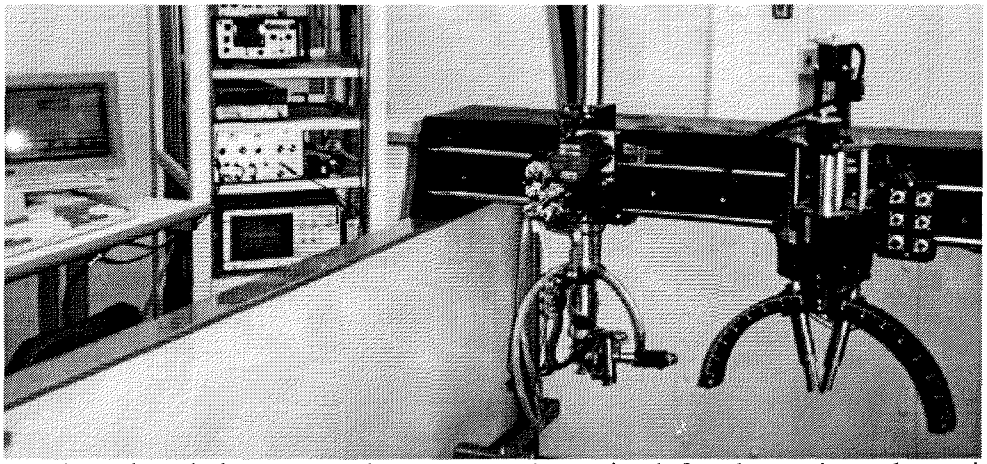
Crane, 1982] phenomena in composites offered effective NDE techniques and progress in the field enabled significant quantitative capability. These obliquely insonified ultrasonic wave techniques were studied both experimentally and analytically by numerous investigators [e.g., Mal & Bar-Cohen, 1988, Nayfeh & Chimenti, 1988, and Dayal & Kinra, 1991]. These studies led to the development of effective quantitative NDE methods for the determination of the elastic properties, for accurate characterization of defects and even for the determination of the quality of adhesively bonded joints [Bar-Cohen, et al, 1989]. Parallel to the development of the analytical capability, jointly with Mal from UCLA [Mal, 1988], extensive efforts have been made to enhance the LLW experimental capability and the progress is reported herein. In spite of the progress that was made both theoretically and experimentally, oblique insonification techniques have not yet become standard industrial NDE methods for composite materials. The authors investigated the possible causes that are hampering the transition of the LLW technique to practical NDE and address the key issues that are associated with the experimental capability.

LEAKY LAMB WAVE PHENOMENON

The leaky Lamb wave (LLW) phenomenon is induced when a pitch-catch ultrasonic setup insonifies a plate-like solid immersed in fluid. This phenomenon was discovered while testing a composite laminate using Schlieren imaging system [Bar-Cohen, et al, 1993]. The phenomenon is associated to a resonant excitation of plate waves that leak waves into the coupling fluid and interfere with the specular reflection. The leaky waves modify the reflection spectrum introducing a series of minima produced by a destructive interference at specific frequencies between the leaky wave and the specular reflection. The LLW experimental procedure involves measurement of the reflections and extraction of the dispersive spectral characteristics at various angles of incidence and at several orientations (polar angles) with the laminate fibers. The data is presented in the form of dispersion curves showing the LLW modes phase velocity (calculated from Snell's law and the angle of incidence) as a function of the frequency. Bar-Cohen and Chimenti [1984] investigated the characteristics of the LLW phenomenon and its application to NDE. These investigators concentrated on the experimental documentation of observed modes and the effect of defects. Their study was followed by numerous theoretical and experimental investigations of the phenomenon [e.g., Nayfeh & Chimenti, 1988, Mal & Bar-Cohen, 1988, and Dayal & Kinra, 1991]. A method was also developed to invert the elastic properties of unidirectional composite laminates from the LLW dispersion data [Mal, 1988; and Mal & Bar-Cohen, 1988] and the study was expanded to NDE of bonded joints [Bar-Cohen, et al, 1989].

The experimental acquisition of dispersion curves for composite materials requires accurate control of the angle of incidence/reception and the polar angle with the fibers. To perform these measurements rapidly and accurately was addressed by the principal author where a specially designed LLW fixture was developed [Bar-Cohen, et al, 1993]. With the aid of a personal computer, the LLW fixture (made by QMI, Costa Mesa, CA) controls the height, angle of incidence and polar angle of the pitch-catch setup. The LLW fixture manipulates the angle of incidence/reception simultaneously while maintaining a pivot point on the part surface. A view of the fixture installed on a C-scan unit is shown in Figure 1. A computer code was written to control the incidence and polar angles, the height of the transducers from the sample surface's, and the transmitted frequency. In prior studies, the data acquisition involved the use of sequentially transmitted tone-bursts at single frequencies over a selected frequency range (within the 20dB level of the transducer pair). The reflected signals are acquired as a function of the polar and incidence angle and are saved in a file for analysis and comparison with the theoretical predictions. The minima in the acquired reflection spectra represent the LLW modes and are used to determine the dispersion curves (phase velocity as a function of frequency). The incident angle is changed incrementally within the selected range and the reflection spectra are acquired. For graphite/epoxy laminates the modes are identified for each angle of incidence in the range of 12^o to 50^o allowing the use of free-plate theoretical calculations. At each given incidence angle, the minima are identified, added to the accumulating dispersion curves, and plotted simultaneously on the computer display. While the data acquisition is in progress, the acquired minima are identified on both the reflection spectra and the dispersion curves.

A follow-on study by [Bar-Cohen, et al, 1993] showed that the capability to invert the elastic properties using LLW data is limited to the matrix dominated stiffness constants. This limitation can be partially overcome if the incidence angle can be induced at less than 10^o, but this is difficult if not impossible too achieve in a practical experiment. An alternative method based on pulsed ultrasonics was developed by Bar-Cohen, Mal and Lih [1993]. Assuming that the material is transversely isotropic and using pulses in pitch-catch and pulse-echo experimental arrangements, it was shown that all the five elastic constants can be determined fairly accurately. A parametric study



was conducted and the expected error was determined for the various determined constants in relation to experimental errors. It was also shown that that stiffness constant, C_{12}, that is the most sensitivity to defects, is critically sensitive to alignment errors in the incident and polar angles. While the developed capability allowed measuring dispersion curves to support the analytical efforts, the process has been still slow and there were difficulties identifying modes associated with minima that are less than about 4% below the adjacent signal.

FIGURE 1: A view of the LLW scanner (bridge right side) installed on the JPL's C-scan system.

RAPID LLW DISPERSION DATA ACQUISITION

Extensive studies of composites by the authors and their colleagues led to the identification of a series of deficiencies that affect the inversion reliability and the transition of the technique to practical application. Their recent efforts concentrated on the enhancement of the speed of the data acquisition and the number of modes that can be identified in a LLW experiment. Since the process of acquiring the spectrum was identified as time consuming with a series of redundancies, the transmitted signals was modified to using FM modulated pulses that are induced sequentially within the required spectral range. A trigger based on the selected time frame is transmitted to synchronize the reflected signals on the data acquisition scope and the time domain signal is converted to a spectral data. The function generator also provides a reference frequency marker for the calibration of the acquired data when converting the signal from time to frequency domain. A digital scope is used to acquire the reflection spectral data after being amplified and rectified by an electronic hardware. The signals that are induced by the transmitter are received, processed and analyzed by a personal computer after being digitized. The reflected spectra for each of the desired angles of incidence is displayed on the monitor and the location of the minima (LLW modes) are marked by the computer on the reflection spectrum. The algorithm of identifying the minima was modified to employ reliably smaller level signals, which are associated with more diffused modes. The identified minima are accumulated on the dispersion curve, which is shown on the lower part of the display.

The use of the FM modulation and automatic optimal adjustment of the transducers' height significantly increased the speed and accuracy of acquiring LLW dispersion curves. To compare the performance, 20 different angles of incidence were acquired in about 45 seconds as oppose to over 15-minutes using the former approach. An algorithm that is based on the Simplex inversion methodology was already programmed into the computer software and was used to extract the stiffness constants. Once the dispersion data is acquired, the inversion option of the software is activated and the elastic stiffness constants are determined as shown in Figure 2a. The material is AS4/3501-6 and the polar angle (i.e., the direction of Lamb wave propagation) is 0°. The reflected spectrum for 39.9° incident angle is shown at the top of this Figure, and the accumulating dispersion curves are at the bottom. Using the system with the enhanced capability, various defects can be detected and characterized rapidly based on the signature and quantitative data that is available from the dispersion curves. In Figure 2a, the response from a defect-free graphite/epoxy laminate tested at the 0-degree polar angle is shown. In Figure 2b, the response from an area with a layer of simulated porosity (microballoons) is presented. As expected, at low frequencies the porosity has a relatively small effect and the dispersion curve appears similar to the one on Figure 2a. On the other hand, as the frequency increases, the porosity layer emulates a delamination and modifies the dispersion curve to appear the same as half the thickness laminate.

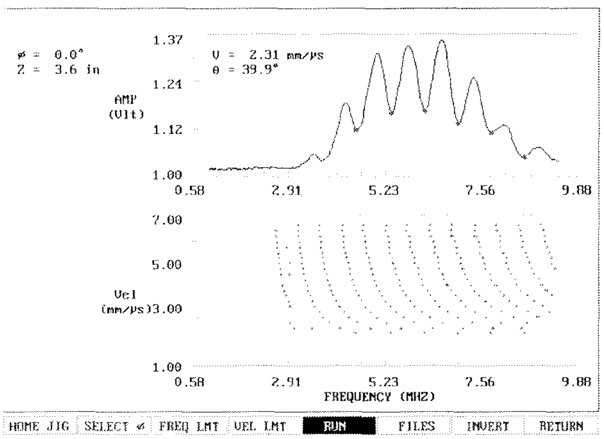


FIGURE 2a: The refection at 39.5 degrees incidence angle and the dispersion curve for a Gr/Ep $[0]_{24}$ laminate with no defects

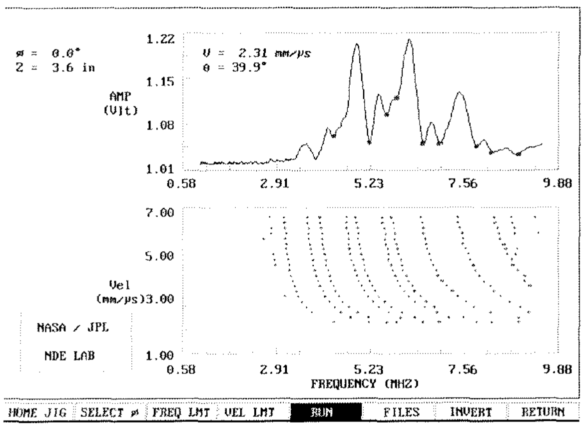


FIGURE 2b: The response at a defect area where porosity was simulated at the middle layer.

To enhance the accuracy of material stiffness constant inversion, a method was developed to acquire dispersion curves and displaying them as shown in Figure 3. In this Figure a 3.125-mm unidirectional laminate was tested along the fibers polar angle. Using this capability the unidirectional laminate was also tested along the 90^{0} polar angle. As can be seen in Figure 4 modes that otherwise would be considered noise are clearly identified. To demonstrate this capability further a 1.6-mm aluminum plate was tested in the low frequency region near the first symmetric and antisymmetric modes. As shown in Figure 5 the portion of the mode that is almost parallel to the frequency axis is identified offering a capability that was highly difficult when analyzing the signals in the single frequencies as conventionally done. This method was found to allow viewing modes with amplitude levels that are significantly smaller than ever observed before. The bright curved lines show the modes on the background of the reflected spectra. Methods of extracting the modes were investigated using image processing operators and neural network procedures. Once the curve of a specific mode is determined, it is transformed to actual frequency vs. velocity data and then inversion is applied.

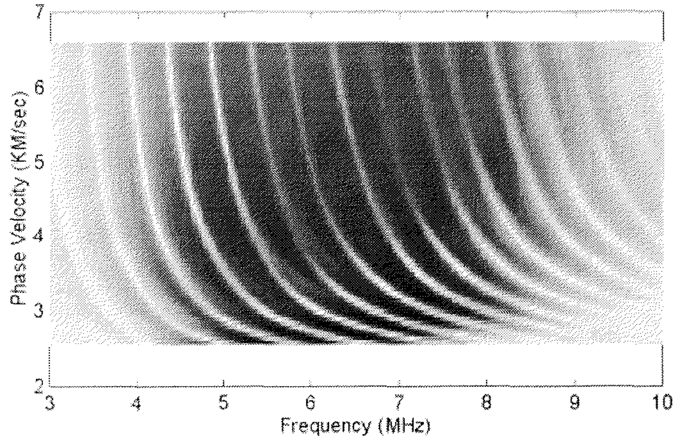


FIGURE 3: A view of an imaging method of presenting LLW dispersion curve for unidirectional Gr/Ep along the fibers.

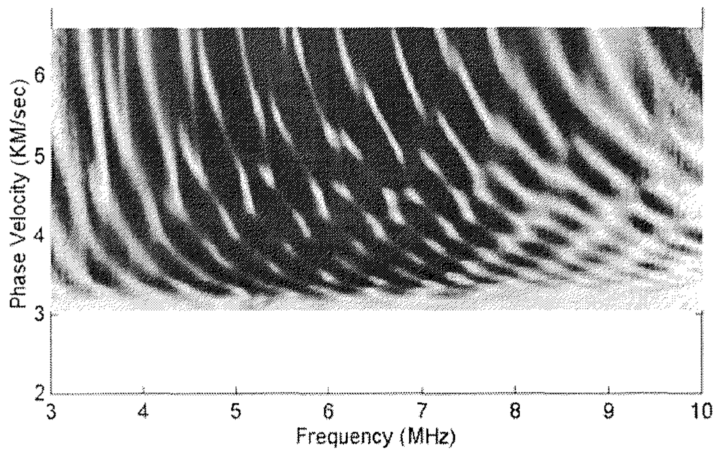
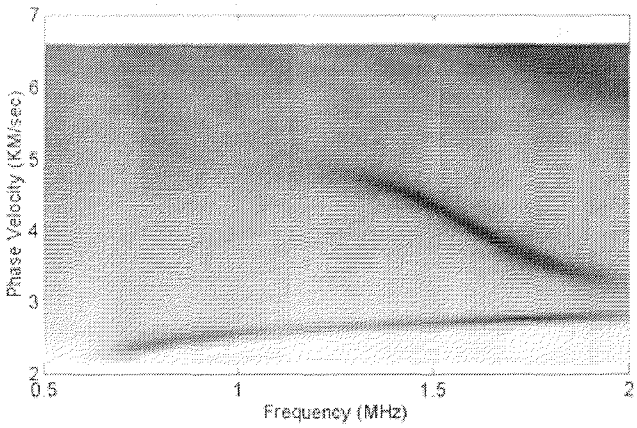


FIGURE 4: A view of the dispersion curve for the laminate shown in Figure 3 along the 90^{0} polar angle.

FIGURE 5: A view of the first symmetric and antisymmetric modes using dispersion curve graphical presentation.



ISSUES AFFECTING THE TRANSITION OF LLW TO PRACTICAL USE

For over 17 years since the discovery of the LLW phenomenon it has been studied extensively both analytically and experimental. However, in spite of the successful results the technique is still not being used for practical NDE. The authors examined the causes that may hamper the transition of the LLW method to standard NDE application and identified the following possible key issues:

1. Material density - The inverted material constants are based on the assumption that the material density is known. This assumption may not be correct particularly in the presence of flaws. NDE measurement of the material density can be done by radiographic tests. However, such tests are not economical and they require access from two sides of the test structure, therefore an alternative method of measuring the density is needed.
2. Multi-orientation laminates - The inversion algorithm developed for the determination of the elastic properties has been very successful for unidirectional laminates. The analysis of laminates with multi-orientation layers using ply-by-ply analysis is complex and leads to ill-posed results. Methods of inverting the material elastic properties without the necessity to deal with individual layers are needed and they are currently being explored.
3. Complex data acquisition - The LLW data acquisition setup is complex and the related process is not user friendly. The authors have significantly improved the data acquisition process by automating the process of aligning the height of the setup as discussed in this manuscript. Also, the polar angle is set using the polar backscattering technique [Bar-Cohen and Crane, 1982] to determine the direction of the first layer. User friendly control software that operates on the Widows platform is being developed to allow interactive software control and minimize the need for manual alignment of the setup.
4. Time-consuming process - The formerly reported process of acquiring dispersion curves was time consuming and took between 10 and 20 minutes to acquire a curve for a single point on a composite material. As reported in this manuscript, recent development by the authors allows measuring dispersion curves at a significantly higher speed in the range of fraction of a minute.

Using this new capability, various defects can be detected and characterized based on their dispersion curve signature. Further, the increased speed of dispersion data acquisition offers the capability to produce C-scan images where variations in individual stiffness constants can be mapped.

CONCLUSIONS

The leaky Lamb wave (LLW) method has been studied by numerous investigators who contributed significantly to the understanding of wave behavior in anisotropic materials. However, in spite of the progress and researchers success, the LLW method is still far from being an acceptable standard NDE method. The authors examined the potential issues that are hampering this transition to practical NDE and identified 4 key issues. These issues include: a) There is a need to determine the density nondestructively using access from a single-side; b) The inversion technique of determining the elastic stiffness should be applicable to multi-layer composites treating it terms of global properties; c) The data acquisition process needs to be more user friendly; and d) The process of data acquisition needs to be faster. The authors have made significant progress in simplifying the data acquisition process and the acquisition speed with some progress being made in dealing with cross-ply and quasi-isotropic laminates. The inability to measure the material density with an NDE tool using access from a single side of a laminate is still considered an unresolved issue and will require further research.

ACKNOWLEDGMENT

The research at Jet Propulsion Laboratory (JPL), California Institute of Technology, was carried out under a contract with National Aeronautics Space Agency (NASA). The authors would like to thank Prof. Ajit Mal from UCLA for his contributions to the analytical capability of inverting stiffness data.

RERFERENCES

Bar-Cohen, Y., and R. L. Crane, "Acoustic-Backscattering Imaging of Subcritical Flaws in Composites," Materials Evaluation, Vol. 40, No. 9 (1982), pp. 970-975.

Bar-Cohen, Y., and D.E. Chimenti, Review of Progress in Quantitative NDE, Vol. 3B, D. O. Thompson & D.E. Chimenti (Eds.), Plenum Press, New York and London (1984), pp. 1043-1049.

Bar-Cohen, Y., A.K. Mal and C. -C. Yin, Journal of Adhesion, Vol. 29, No. 1-4, (1989), pp. 257-274.

Bar-Cohen, Y., et al, "Ultrasonic Testing Applications in Advanced Materials & Processes," Nondestructive Testing Handbook, Section 15 in Vol. 7: Ultrasonic Testing, Section 8, A. Birks and B. Green Jr. (Ed.), American Society for NDT, Columbus, OH (1991) pp. 514-548.

Bar-Cohen, Y., A. Mal, and S.-S. Lih, "NDE of Composite Materials Using Ultrasonic Oblique Insonification, Materials Evaluation, Vol. 51, No. 11, (1993), pp.1285-1295.

Bar-Cohen Y., and P. Backes, "Open-architecture robotic crawlers for NDE of aircraft structures," Materials Evaluation, Vol. 57, No. 3 (1999) pp.361-366.

Dayal, V., and V.K. Kinra, J. Acoustic Soc. of Amer., Vol. 89, No. 4 (1991), pp. 1590-1598.

Mal, A. K., "Wave Propagation in Layered Composite Laminates under Periodic Surface Loads." Wave Motion, Vol. 10, (1988), PP. 257-166.

Mal, A. K., and Y. Bar-Cohen, Proceedings of the Joint ASME and SE meeting, AMD-Vol. 90, A. K. Mal and T.C.T. Ting (Eds.), ASME, NY, (1988), pp. 1-16.

Mal, A. K., C. -C. Yin, and Y. Bar-Cohen, "Ultrasonic NDE of Cracked Composite Laminates," Composites Engineering, Pergamon Press, Vol. 1, No. 2, (1991), pp. 85-101.

Nayfeh, A. H., and D. E. Chimenti, J. Applied Mechanics, Vol. 55 (1988) p. 863.